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## **THERMOCAPILLARY CONVECTION IN BUBBLES AND DROPS**

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### **ABSTRACT**

When bubbles or drops are present in an immiscible liquid in reduced gravity and the temperature of the liquid is non-uniform, a thermocapillary stress is generated at the interface due to the variation of interfacial tension with temperature. The resulting flow propels the drop freely suspended in the liquid towards warmer regions, so as to minimize the interfacial energy.

The literature on thermocapillary migration is discussed in detail in Subramanian and Balasubramanian (2001). The motion of a drop neglecting the convective transport of momentum and energy was analyzed in the pioneering study by Young, Goldstein and Block (1959). In this presentation, we will focus on the effect of convective transport of momentum and energy, that are characterized by the Reynolds number and the Marangoni number, respectively. The results of asymptotic analyses for the speed of the drop for low and large values of these parameters will be discussed. These predictions as well as those

from numerical simulations will be compared with reduced gravity experimental results obtained from experiments performed aboard the space shuttle.

The following topics will be discussed as well. The first topic is the effect of Newtonian surface rheology of the interface and contributions from stretching and shrinkage of the interfacial area elements, when the interfacial elements are in motion. The former occurs because of dissipative processes in the interfacial region such as when surfactant molecules are adsorbed at the interface in sufficient concentration. The interface is typically modeled in this instance by ascribing a surface viscosity to it (Scriven, 1960). This is a different effect from interfacial tension gradients arising from surfactant concentration gradients. The stretching and shrinkage of interfacial area elements leads to changes in the internal energy of these elements that must be provided by the fluids adjoining the interface. When an element on the interface is stretched, its internal energy increases. This energy is supplied by the neighboring fluids, which are cooled as a conse-

quence. Conversely, when an element on the interface shrinks, the adjoining fluids are warmed. In the case of a moving drop, elements of interfacial area are stretched in the forward half of the drop, and are shrunk in the rear half. Consequently, the temperature variation on the surface of the drop and its migration speed are modified (Harper, Moore, and Pearson, 1967). The analysis of the motion of a drop considering these effects was performed by LeVan (1981) in the limit when convective transport of momentum and energy are negligible. We extend LeVan's analysis to include the convective transport of momentum by demonstrating that an exact solution of the momentum equation is obtained for an arbitrary value of the Reynolds number.

The second topic is the instability of a stationary bubble when a surface chemical reaction takes place that consumes heat. The energy must be supplied by the surrounding liquid. The analysis by Kurdyumov, Rednikov and Ryazantsev (1994) shows that the stationary state of the bubble is unstable to a perturbation in the position of its center of mass when the Marangoni number exceeds a critical value. Thus an autonomous motion of the bubble can ensue. The direction of motion of the bubble cannot be specified. A linear analysis only predicts the critical Marangoni number, but not the speed of the bubble. A weakly non-linear analysis has been performed by Rednikov, Ryazantsev and Velarde (1994) to obtain the migration velocity. We analyze the problem for the migration speed of a bubble assuming that the post-critical motion is such that the Reynolds and Marangoni numbers are large compared large compared with unity.

## References

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